THE RIA DRIVER LINAC*

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Abstract

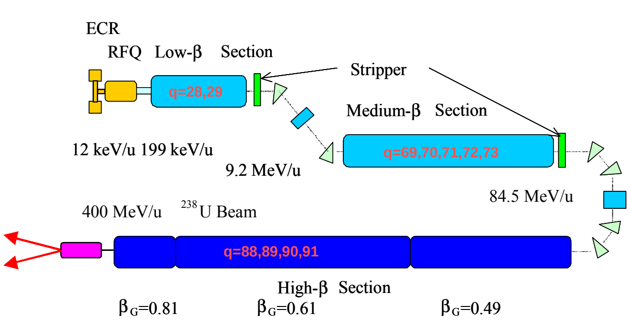
The driver linac for the U. S. RIA project will be a 1.4 GV superconducting linac capable of accelerating the full mass range of ions from 900 MeV protons to 400 MeV/u uranium, and delivering a cw beam of 400 kW shared by at least two targets simultaneously. Elements of the linac are being developed at several U.S. laboratories. The current status of linac design and development is reviewed with emphasis on changes in the baseline design since the last linac conference.

1 INTRODUCTION

A principal element of the proposed U. S. Rare Isotope Facility (RIA) [1]will be a superconducting (SC), 1.4 GeV ion linac [2,3]capable of accelerating ions of any stable isotope from hydrogen to uranium, and delivering several hundred kW of beam onto production targets at 400 MeV/nucleon or more. Great flexibility is obtained by configuring the driver as an array of short, independently-phased SC cavities. The cavity array can be tuned to provide a variable velocity profile, which provides good efficiency over the full mass range of ions, protons to uranium. The relatively short length of the cavities permits a lattice with frequent transverse focusing elements. This, together with the high gradients available in SC cavities, permits design for very large longitudinal and transverse acceptance, enabling the acceleration of multiple-charge state (multi-Q) beams [2,4,5]. Such multi-Q operation increases the available current for ion-source-performance limited beams, by more than a factor of 10 for uranium, and also enables the use of multiple strippers, reducing the size and cost of the linac.

The elements of the linac are shown schematically in Fig. 1. The following describes the machine as configured for a beam of uranium ions:

Figure 1: Elements of the driver linac



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- The first section consists of an ECR ion source on a 100 kV voltage platform, from which charge states 28 and 29 + are extracted, bunched into alternate buckets at 57.5 MHz, and injected into a short cw normally-conducting RFQ.
- At an energy 0.2 MeV/A, the beam enters the low-β section of the linac, an array of 68 SC drift-tube cavities of types 1 through 4 as shown in Fig. 2.
- At an energy of 9.2 MeV/A the beam is stripped, and the 5 charge states 69 through 73 + selected out in the bend region.
- The medium-β section, an array of 160 cavities of types 5 and 6 (Fig. 2), accelerates the uranium beam to an energy of 88.4 MeV/A.
- The second stripper produces and the bend region selects out 4 charge states, 88 - 91+.
- The final linac section, an array of 166 SC elliptical-cell cavities (types 7 – 9 of Fig. 2), accelerates the beam to a final energy of more than 400 MeV/A.

Table 1 shows parameters for several beams. The linac is tuned differently for different beams, changing the velocity profile to provide higher output energies for the lighter ions.

In what follows, this paper will discuss developments since the last linac conference both in terms of changes in the baseline design and also as a brief outline of several alternative design options that have recently been put forward [6].

2 UPDATED BASELINE DESIGN

Figure 2 shows the nine types of SC cavities required to span the energy range from the injection energy of 0.02 MeV/A from the RFQ, to the output energy of 400 MeV/A and above. Table 2 shows some details of the cavity array, divided into three sections by the charge-stripping stations.

Table 1. Beam parameters for several ion species

Species	Input Charge State	Stripping	Output Energy	Output Power
H	1^+	none	893 MeV/A	400 kW
^{3}He	2^+	none	707	400
D	1^+	none	587	400
^{136}Xe	18^+	twice	461	400
^{238}U	28.5^+	twice	403	102

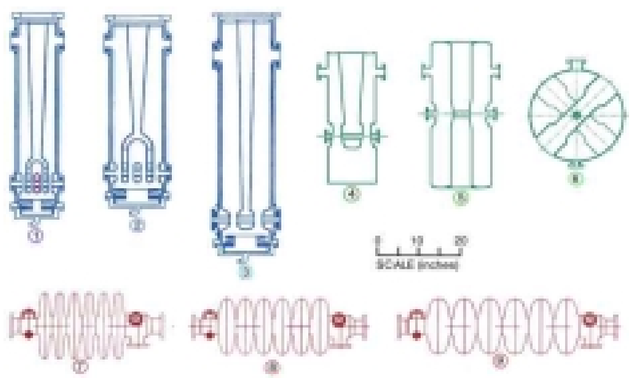

Figure 2. Nine types of superconducting cavities spanning a frequency range from 57.5 to 805 MHz and a velocity range $0.02 < \beta < 0.9$

2.1 Front-end section

Even with multiple charge state beams, the long-range goal of 400 kW of uranium beam requires a significant increase in ECR ion-source [7]performance, which continues to be an important development area for RIA.

Detailed numerical studies [8], including particle tracking through 3-dimensional electromagnetic fields, have confirmed the feasibility of accelerating a two-charge-state beam of uranium from an ECR source. A design has been developed [9,10]for a two-charge-state LEBT, multi-harmonic buncher, and 57.5 MHz RFQ which will produce beams of sufficiently small longitudinal and transverse emittance to permit multiple charge state operation over the full length of the linac.

2.2 Low-velocity section of the SC linac

Both the low and the medium velocity sections are comprised of relatively low-frequency SC cavities operating at a temperature of 4 K.

The three SC cavity types required for the low-velocity section closely resemble already-developed cavities used for many years in SC heavy-ion linacs used for nuclear structure and atomic physics studies[11]. While the RIA driver will call for appreciably higher beam current than present practice, beam intensities are well below the threshold for space-charge effects. Also the relatively large aperture and short focusing period of the SC linac provide very large transverse and longitudinal acceptance, which ensure that beam loss is not a problem. The low-velocity section does not present high-priority development tasks.

Cavity Type	Beta	Frequency	# Cavities
4-Gap	0.02	57.5 MHz	2
4-Gap	0.03	57.5	5
QWR	0.06	57.5	32
QWR	0.15	115	30
Strip uranium beam at 9 MeV/A			
HW	0.26	172.5	88
Spoke	0.4	345	72
Strip uranium beam at 88 MeV/A			
6-Cell	0.47	805	58
6-Cell	0.61	805	80
6-Cell	0.81	805	28

Table 2. Superconducting cavity configuration showing the number of cavities required, assuming 20 MV/m peak surface electric fields in the drift-tube cavities and 27.5 MV/m in the elliptical-cell cavities.

2.3 Medium-velocity section of the SC linac

Correcting transverse steering problems

Of the three cavity geometries originally specified for the medium-velocity section, the first two have had to be substantially modified in order to eliminate beam-steering effects that became problematic in detailed, 3-dimensional simulations of the beam dynamics.

In drift-tube loaded cavities of the quarter-wave-line class (QWR), dipole components of the rf magnetic field can cause sufficient transverse deflection or steering [12] to cause objectionable emittance growth for intense beams or multiple-charge beams. Corrective methods have been found for single-drift-tube but not for multiple-drift-tube QWR structures [13].

To eliminate this problem the baseline design now incorporates a 115 MHz QWR structure with a drift-tube designed to provide a corrective electric dipole field which largely eliminates steering [14]. The next two cavities are of the half-wave class which have no dipole rf magnetic field terms on the beam axis, and do not exhibit appreciable beam-steering.

Higher gradients in SC drift-tube cavities

In recent developments at several laboratories, SC drift-tube cavities have consistently operated at peak surface electric fields of 30 MV/m and above [15,16,17]. In the case of the three spoke-loaded cavities so far tested, excellent performance has been obtained by using high-pressure water rinsing techniques similar to those so successfully developed for the TESLA velocity-of-light SC structures [18] and being developed for elliptical cell cavities for the SNS project [19].

If such field levels can be consistently obtained under on-line operating conditions, the cost of the medium velocity section could be significantly reduced. Performance appreciably below design gradient of the cavities in the low and medium velocity sections of the linac would, however, entail loss of capability to produce useful uranium beams, so that the specification must be highly conservative in this respect. To achieve cost saving by higher gradients without undue risk, therefore, adequate testing of multiple structures under realistic operating conditions will be needed to develop cryomodule systems design and establish reliable assembly and operating procedures.

2.4 High-velocity section of SC linac

The high-velocity section consists of 166 cavities, each with six elliptical cells, operating at 2 K. Two of the three elliptical 6-cell cavity types have been recently developed for the U.S. spallation neutron source (SNS) project [19]. Recent tests [20] of the SNS cryomodule with three $\beta = 0.61$ elliptical-6-cell cavities achieved excellent performance and demonstrated good mechanical stability, not only in pulsed operation, as required for the SNS linac, but also in cw operation, as will be required for the RIA linac

The third elliptical cell cavity type, for $\beta = 0.47$, is currently being developed [21].

3 ALTERNATE DESIGN OPTIONS

. Table 3 compares the number of cavities required, and the performance of three different design options all of which were evaluated assuming operation at 20 MV/m peak surface electric field for all low/mid-β SC cavities, and 28 MV/m peak electric field for all high-β cavities.

3.1 80 MHz Option

An alternate design for the driver linac based on a bunching frequency of 80.5 MHz and a different set of SC cavities has been proposed [6,22]. An advantage of the proposed design is that only four types of drift-tube cavity are required rather than six. This is accomplished in part by replacing one of the SC cavity types with a normally-conducting cw RFQ.

Some disadvantages are that the total number of cavities is increased more than 30% relative to the base-line design, with a commensurate increase in cost, and the linac length would be appreciably increased. The cavity designs proposed in [6] are of a simple cylindrical geometry, but have not been corrected for the beam steering discussed above, as will probably be necessary to control emittance growth and concomitant beam loss and simplify linac tuning procedures.

3.2 Spoke Cavity Option

Another alternate design would use 345 MHz spoke-loaded cavities in place of 805 MHz elliptical-cell structures for the high-velocity section of the driver linac.

Spoke-loaded cavities have peak surface fields comparable or lower than elliptical-cell cavities for design velocities $\beta \leq 0.6$ [23]. Also, because spoke cavities are relatively compact, operation at lower frequency is more convenient. Low-frequency operation is advantageous in several respects:

- For a given number of accelerating gaps (of length $\beta\lambda/2$) the structure is longer. This enables a better tradeoff between the total accelerating voltage and the velocity acceptance of each unit
- The rf losses required to produce a given accelerating voltage are reduced, since the SC surface resistance scales roughly as ω^2.
- For design velocities $\beta \leq 0.6$, spoke cavities are more stable mechanically than elliptical-cell structures

Figure 3 shows a sectioned view of a 345 MHz triple-spoke-loaded SC niobium cavity. Preliminary designs for two triple spoke cavities suitable for the high-velocity section of the RIA driver have been evaluated numeric-ally, yielding the parameters detailed in Table 4.

Using these cavities [24]for the high-velocity section of the RIA driver would could offer several benefits. As shown in Table 3, with spoke cavities, the total cavity count is reduced significantly. Somewhat surprisingly, the spoke cavity option provides significantly higher energy beams of light ions than the elliptical-cell cavity option. The reason for this can be seen in Figure 4, where for comparison the velocity acceptance of the elliptical-cell option is also shown by the lightly-shaded curves. The β

Table 3: Cavity configuration and output beam energies for several design options (see text).

	Benchmark Design	80 MHz Option	3-Spoke Option
number of cavities required			
low/mid β	229	340	169
high β	166	193	170
Total	395	533	339
output beam energy (MeV/A)			
^{1}H	893	891	988
^{3}He	707	710	737
D	588	593	595
^{136}Xe	462	449	451
^{238}U	404	400	404

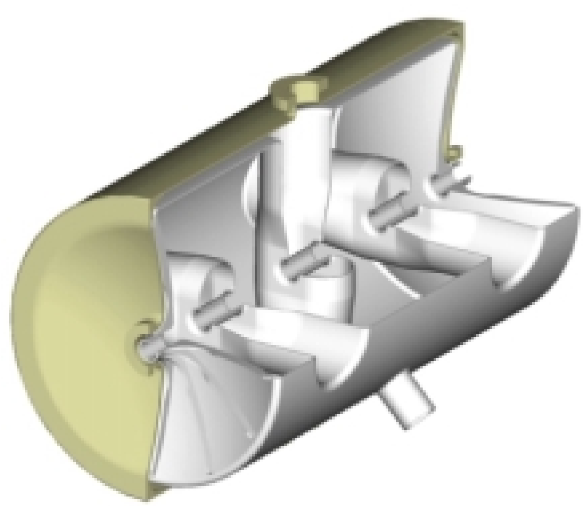

Figure 3: Section view of an 85 cm long, 345 MHz, triple-spoke-loaded niobium cavity for $\beta = 0.62$

Table 4: Parameters for two 3-spoke cavities

β_{GEOM}	0.48	0.62
frequency	345 MHz	345 MHz
length	65 cm	85 cm
QR_S	92	103
at 1 MV/m		
E_{PEAK}	3.0 MV/m	3.1 MV/m
B_{PEAK}	90 G	88 G
RF Energy	356 mJ	582 mJ

0.81 elliptical call cavity provides considerably more accelerating voltage for light-ion, high velocity beams than the β 0.62 spoke structure. Note that this is more than offset by the higher voltage the spoke cavities provide compared with the other two elliptical cell structures. The broader velocity acceptance of the spoke cavities gives better performance in the high-velocity tail. As a result, the spoke cavity design option increases the proton beam energy by nearly 100 MeV.

Finally, primarily because lower frequency operation provides a larger longitudinal 'bucket', the longitudinal acceptance of high velocity section of the linac would be increased by approximately a factor of four by using spoke cavities.

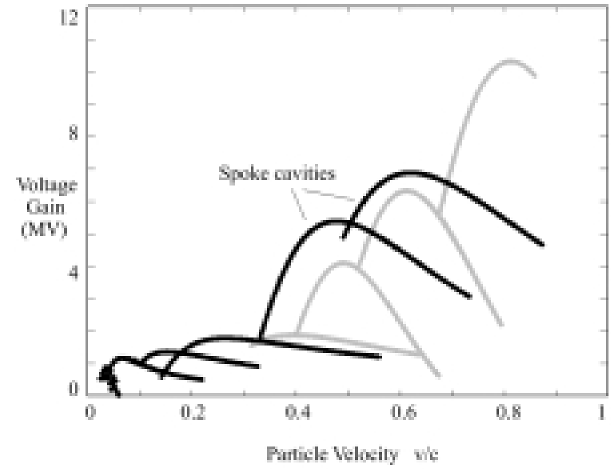

Figure 4: Voltage gain/cavity along the linac for the spoke-cavity option (elliptical-cell option is shaded). Plots for several ion species are superimposed to show the full velocity range required of each cavity type.

4 CONCLUSIONS

A firm technical basis exists for the multi-beam, multiple charge state SC ion driver linac for the RIA project. Ongoing development work is opening further options for improved performance and reduced costs.

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